Inhibiting water infiltration with polyacrylamide and surfactants: Applications for irrigated agriculture

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ABSTRACT: Efficiencies of surface irrigation systems are often limited by infiltration conditions. Treatments that decrease infiltration into unlined canals, reservoirs, and the inflow end of furrows relative to outflow ends would reduce seepage losses and improve application uniformity. Several laboratory studies evaluated effects of high molecular weight (10 to 15 Mg mol^{-1}), water-soluble, anionic polyacrylamide (PAM), alone and combined with anionic surfactants, on the hydraulic conductivity (KSAT) of soils. Dry soils were treated with one or two treatment solutions and subjected to conditions that simulated those in an irrigation furrow or pond. The KSAT of soil packed in columns was measured with a constant head apparatus for 19 hours. PAM treatment concentrations > 125 mg L^{-1} applied to dry soils preceding flooding reduced KSAT by 25%, and a 10 mg-L^{-1} PAM + 29 k-mg-L^{-1} sodium-lauryl-sulfate surfactant application reduced KSAT by 70%, relative to controls. Miniflume tests then applied the treatments only to the inflow end of the mini-furrows. The 125 and 250 mg L^{-1} PAM treatments significantly improved water application uniformity: Cumulative infiltration was reduced in the upper half of miniflume furrows and increased in the lower, relative to controls. When applied to dry soils and allowed to dry overnight, as may be done when treating irrigation ponds, the 1,000 mg L^{-1} PAM solution reduced KSAT by 60% to > 90% in silt loam and clay loam soils. Either the single or combination treatments could potentially be used to increase the uniformity of furrow water applications and reduce seepage from unlined irrigation ponds and canals.

Keywords: Furrow irrigation, infiltration, irrigation uniformity, PAM, polyacrylamide, sealing

Increasing competition for limited water resources and a need to improve groundwater quality motivates water managers to reduce irrigation water losses from deep percolation. Two specific means of doing this are reducing seepage losses from soil-lined distribution channels and increasing surface irrigation application uniformity (Bucks et al., 1990). About 17% (89.3 M m^3 day^{-1}, or 72,400 ac ft day^{-1}) of water diverted for irrigation is lost in conveyance (U.S. Geological Survey [USGS], 1990). Seepage losses from soil-lined distribution channels range from 10% to 50% of the flow. Economical methods are needed to reduce these losses. Furrow irrigation produces a less-uniform water application across the field than level-basin or sprinkler irrigation (Kruse et al., 1990). Infiltration opportunity time is greater at the inflow end of furrows than at the outflow end. To irrigate the entire field sufficiently requires excessive water application to the inflow-end soils, which increases the water, nutrients, and agrochemical leaching potential at the inflow end relative to that at the outflow end. One means of solving this problem is to alter the spatial pattern of infiltration along the length of the furrow, decreasing infiltration at the furrow inflow end and/or increasing it at the outflow end.

Inhibiting infiltration into soil-lined channels can be effectively accomplished by lining them with concrete or membranes of rubber, plastic, or bitumin. Such methods are costly. Less expensive approaches may treat canal surfaces with sealing agents in small but effective doses or add the agent to the initial water flows, which carries the agent to the canal perimeter during filling. The addition of silt or clay to irrigation flows can inhibit infiltration in canals but has not met with consistent success (Withers and Vipond, 1980). High molecular weight polymer treatments and surfactants alter conductivity of porous media to water. Water-soluble anionic polyacrylamides (PAM) are typically used in irrigation water because they are more environmentally inert than cationic polymers.

Polymer treatments can either increase or decrease water infiltration into soils, depending on the type and concentration of polymer applied, soil type, and application protocol. Infiltration of high molecular weight (10 to 15 Mg mol^{-1}, or 13 to 16.5 ton mol^{-1}), anionic PAM solutions ponded on dry loamy sand or presaturated sand columns decreased with increasing PAM concentration from 0 to 400 mg L^{-1} (0 to 400 ppm) (Malik and Letey, 1992; Falatah et al., 1999). Infiltration decreases were greater with increasing polymer charge density, which was attributed to increased viscosity associated with higher charge (Malik and Letey, 1992).

Experiments that focused on finer-textured, more structured soils have evaluated infiltration using several water application methods. Researchers treated soils with 0 to 500 mg L^{-1} (0 to 500 ppm) PAM solutions, allowed soils to dry, and monitored infiltration/conductivity under ponding (Wallace et al., 1986; Malik et al., 1991), furrow irrigation (Mitchell, 1986), or simulated rainfall (Shainberg et al., 1990, 1992). Contrary to that observed for sands, hydraulic conductivity for these treated, structured soils increased with increasing PAM solution concentration, with a relatively greater increase observed for medium-textured soils than for fine-textured soils (Shainberg et al., 1990, 1992).

A different PAM application technique on structured soils was used with furrow (Lentz et al., 1992, 2002; Trout et al., 1995; Lentz and Sojka, 2000) and sprinkler irrigations (Bjorneberg and Aase, 2000). Researchers added 0 to 20 mg L^{-1} (0 to 20 ppm) PAM to the first irrigation water applied to the dry soils and, instead of waiting for the treated soil to dry, immediately began the irrigation. Under these conditions, PAM tended to increase water intake relative to that of untreated soils. A single 10 mg L^{-1} (10 ppm) PAM treatment applied in the first irrigation

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water produced less consistent infiltration increases than continuous < 1 mg L^{-1} (< 1 ppm) PAM treatments, relative to controls (Trout et al., 1995; Lentz et al., 2002). Higher molecular weight PAM treatments produced smaller infiltration gains than lower molecular weight PAMs. This was attributed to the fact that viscosity of PAM solutions increases with the polymer's molecular weight (Lentz and Sojka, 2000).

Other researchers sprinkled 0 to 50 mg L^{-1} (0 to 50 ppm) PAM solutions onto structured soils that were presaturated with water. Little or no effect of anionic PAMs on infiltration was observed, though cationic polymers significantly increased infiltration (Ben-Hur and Letey, 1989; Ben-Hur et al., 1990, 1992).

Surfactant effects on water infiltration and on percolation in soils is a function of soil type and surfactant characteristics (Kuhnt, 1993). When mixed with sands or clayey soils, surfactants reduced capillary rise of water in soil columns by decreasing water surface tension (Law et al., 1966; Smith and Gillham, 1999). This resulted in reduced retention of soil water and increased depth of infiltration (Karagunduz et al., 2001). Cationic and anionic forms produced a greater effect than nonionic surfactants (Law et al., 1966). Surfactant-treated solutions applied to dry sand columns increased infiltration rates into hydrophobic media but had no effect, or slightly decreased infiltration, into hydrophilic sands (Pelshek et al., 1962). However, when Allred and Brown (1994) continuously applied > 0.001 mol kg^{-1} (> 0.0004 mol lb^{-1}) surfactant solutions to presaturated sand and loam soil columns, the surfactant treatments produced significant conductivity reductions compared with untreated water. Conductivity reductions from surfactant treatments have been attributed to increased soil-solution viscosity, surfactant adsorption, precipitation (Allred and Brown, 1994), and micelle formation (Miller et al., 1975), or increased soil dispersion and aggregate destabilization (Mustafa and Letey, 1969). Lignosulfonate is one of the most inexpensive anionic surfactants available, can be obtained in large quantities (Rosen, 1989), and has been shown to decrease water penetration into lateritic sandy loam soil (Sen and Bhadoria, 1987).

I hypothesized that a one-time application of solutions containing > 50 mg L^{-1} (> 50 ppm) PAM and/or surfactants could be used to inhibit infiltration of untreated irrigation water into structured soils. Such treatments may potentially provide convenient and economical methods for improving water application uniformity in irrigated furrows and reducing water seepage losses from irrigation canals and ponds.

Methods and Materials

Four laboratory experiments tested the above hypotheses. Experiment 1 was a soil column study that used undisturbed soil cores to evaluate the efficacy of various PAM solution concentrations and types of surfactants for reducing infiltration. Soils were not presaturated, and surfaces were stirred to a shallow depth to simulate flow shear. Experiment 2 selected the most promising treatments from Experiment 1 and evaluated their infiltration-inhibiting abilities under conditions expected in an irrigation furrow. To reduce variability, Experiment 2 protocol was changed; soil columns were prepared by packing and, except for a dry surface layer added immediately before measurement, were presaturated. Experiment 3 devised a strategy for applying these treatments to furrow-irrigated fields and used miniflumes to test their effectiveness for improving water application uniformity. Experiment 4 evaluated similar treatments under conditions expected during application to irrigation ponds or canals for four different soil types. This soil column study used packed soil columns, as in Experiment 2, but: 1) columns were saturated after the initial treatment application had dried; 2) soil surfaces were not disturbed by stirring; only the water ponded on the soil was stirred; and 3) sediment was suspended in initial inflows.

Soils, polymers, and surfactants. Soils used in this study are described in Table 1. Portneuf silt loam, coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcids, collected at Kimberly, Idaho, is similar to many of the irrigated soils in the Pacific Northwest of the United States. In Experiment 4, three other types of soils were evaluated: Killpack Variant silt loam, fine-silty, mixed calcareous, mesic, Typic Torriorthent, Montrose County, Colorado; Tauntan loamy fine sand, coarse-loamy, mixed, superactive, mesic Xeric Haplodurids, Gooding County, Idaho; and Roza clay loam, fine, smectitic, mesic, Xerertic Haplocambids, Twin Falls County, Idaho. These soils incorporate a range of soil textures. Calcium is the dominant exchangeable base in the soils, except for Killpack Variant, for which sodium is the dominant exchangeable base.

Surfactant and polymer materials used are identified in Table 2. An anionic polyacrylamide polymer with 18% charge density and 12 to 15 Mg mol^{-1} (13-16.5 ton mol^{-1}) molecular weight (Superfloc®) A-836 CYTEC Industries Inc., Stamford, Connecticut[1]) was used because this a common polymer employed in agriculture to control irrigation-induced erosion. A cationic polymer was also included in Experiment 1 to determine the interaction between it and a nonionic surfactant. Testing of this particular combination had not been

Table 1. Characteristics of soils evaluated in study.

	Texture	Sand† g kg^{-1}	Silt† g kg^{-1}	Clay† g kg^{-1}	pH‡	EC‡ S m^{-1}	OC§ g kg^{-1}	Soluble cations¶ mmolc kg^{-1} Na	Mg	K	Ca	SAR [mmolc L^{-1}]0.5
Portneuf	silt loam	240	560	200	7.3	0.4	8.8	3.6	14.7	1.3	20.1	0.9
Killpack Var.	silt loam	150	730	120	7.8	1.1	4.2	78.3	4.9	0.6	23.5	20.8
Taunton	loamy fine sand	880	50	70	8.0	0.4	1.3	14.7	8	2.3	15.1	4.3
Roza	clay loam	295	370	335	6.4	0.1	8.3	0.8	1	.7	1.9	0.5

† Particle size analysis: hydrometer method applied after removal of organic matter.

‡ Determined on saturated extract.

§ Organic carbon determined using dry combustion after pretreatment to remove inorganic carbon (Shimadzu Total Carbon Analyzer).

¶ Analyzed saturated soil extract using an atomic adsorption spectrophotometer.

Table 2. Surfactant treatments applied in part two of Experiment 1.

Treatment Code	Type	Chemical name	Chemical formula	Source or trade name	Mole. weight g mol^{-1}	Critical micelle conc. mol L^{-1}	Solution conc.
Control	—	Irrigation water	H20	—	—	—	—
An-A	anionic surfactant	Sodium Lauryl Sulfate	$C_{12}H_{25}$-O-SO_3Na	Sigma	288	0.009	28.8 g L^{-1}
An-B	anionic surfactant	Sodium C14-16 Alpha Olefin Sulfonate	$C_{12}H_{20}$-SO_3Na + $C_{14}H_{22}$-SO_3Na	Witconate AOS†	324	0.0013	8.3 g L^{-1}
Non	nonionic surfactant	Alkyl Polyoxyalkylene Glycol Ether	$C_{10}H_{20}(OCH_2CH_2)_7$-$(OCH_2CH_2\ CH)_6$-OH	Witconol 1206	825	0.0001	3.2 g L^{-1}
Cat-P	cationic polymer	Poly(diallyldimethylam-monium chloride)	$[C_6H_{12}NCl]_{98n}$-$[C7H_{14}NCl]_{2n}$	Superfloc C591‡	200k	—	3.5 mg L^{-1}
Non + Cat-P	combined	—	—	—	—	—	Non, 3.2 g L^{-1} Cat-P, 3.5 mg L^{-1}

† Witco Corp., Houston, Texas

‡ CYTEC Industries Inc., Stamford, Connecticut

previously reported in the literature. Anionic and nonionic surfactants were included because these generally have lower toxicities than cationic forms (Gloxhuber, 1974).

Experiment 1: Evaluating PAM concentration and surfactant effects. Undisturbed, 7.5 cm (3 in) diameter, 7.5 cm (3 in) long Portneuf silt loam (Table 1) soil cores were collected from the field and allowed to air dry for four days before treatment. An empty cylinder was attached to the top of the core sample cylinder with a wide rubber band, and the unit was placed on a constant head apparatus like that used for measuring hydraulic conductivity (Klute and Dirksen, 1986). The apparatus and source water supply was placed in a constant temperature room. Flow measurements were taken at an ambient temperature of 27(± 1°C (81(± 0.5° F). The treating solution was gently applied to the soil surface creating an initial ponded depth of 5 cm, or 2 in (218 mL, or 7.4 oz). When 4.5 cm (1.8 in) of the solution had infiltrated into the soil, a flow of untreated water at a constant head of 5 cm (2 in) was applied to the soil cores. The simulated irrigation water used had an electrical conductivity of 0.04 S m^{-1} (0.4 mmho cm^{-1}) and sodium adsorption ratio of 1.3 [mmol$_c$ L^{-1}]$^{0.5}$, and was prepared by diluting tap water 1:1 with reverse osmosis water. Flows were measured over 30 minute intervals after values had stabilized (60 to 90 minutes). The surface soil was then stirred to a depth of 1 cm (0.4 in) with a metal rod to simulate soil disturbance caused by flow shear in irrigated furrows, and flows were measured again. Throughflow was assumed equal to infiltration and reported as mm of water infiltrated per hour. Three to six replicate cores were processed for each treatment. Two sets of treatment solutions were prepared: 1) a series of aqueous solutions with 0, 10, 50, 250, and 500 mg L^{-1} (0, 10, 50, 250, and 500 ppm) water-soluble PAM; and 2) a series of solutions comprising different surfactants and/or a cationic polymer, as described in Table 2. The two treatment sets were applied in two trials using completely randomized designs. Analysis of variance tested for treatment effects on the infiltration response before and after surface disturbance, and the before minus after flow-difference value, with mean separations made at the P=0.05 probability level.

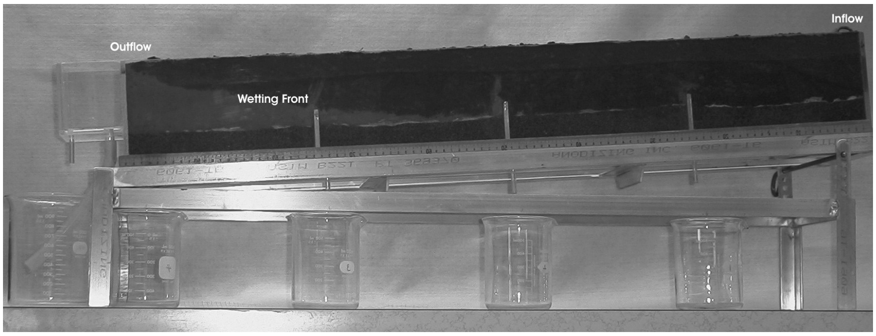
Table 3. Treatments applied in Experiment 2.

	First treatment application			Second treatment application				
Treatment Code	Material applied	Concentration mg L^{-1}	Volume mL	Material applied	Type	Source or trade name	Conc. mg L^{-1}	Volume mL
P10	anionic polymer†	10	40	irrigation water	—	—	—	—
P250	anionic polymer†	250	20	irrigation water	—	—	—	—
P500	anionic polymer†	500	20	irrigation water	—	—	—	—
P10 + S3k	anionic polymer†	10	40	Sodium Lauryl Sulfate	anionic surfactant	Sigma	3 k	20
P10 + S29k	anionic polymer†	10	40	Sodium Lauryl Sulfate	anionic surfactant	Sigma	29 k	20
P10 + LIG	anionic polymer†	10	40	Calcium Lignosulfonate	anionic surfactant	Lignosite 100‡	403 k	30

† Water soluble polyacrylamide: 13-15 Mg mol^{-1}; 18% charge density; Superfloc® 836A; CYTEC Industries Inc., Stamford, Connecticut

‡ Georgia-Pacific West, Inc., Bellingham, Washington

Figure 1
Miniflume apparatus during an untreated "mini-irrigation" of Portneuf silt loam.



Experiment 2: Testing under a furrow irrigation scenario. This experiment was meant to simulate furrow conditions in which soils are loosened then lightly packed during the furrow-forming process. An initial PAM dose was included for non-PAM infiltration treatments, assuming that erosion control would be a desired ancillary goal of the potential field practice.

Portneuf silt loam soil was air-dried, sieved through a #10 screen (2 mm, or 0.08 in, opening), and a 100 g (0.22 lb) portion placed into a 40 mm inside diameter (I.D.) by 133 mm (1.6 in I.D. by 5.2 in) long PVC cylinder. Soils were packed by striking the cylinder base firmly against a solid countertop 10 times. To reduce variability caused by entrapped air, we slowly saturated the soil column with simulated irrigation water, 6 to 12 hours. The saturated soil in each column was covered with 25 g (0.06 lb) of air-dried, 1 to 5 mm diameter (0.04 to 0.2 in diameter) soil aggregates and immediately dosed with an initial treatment of 20 to 40 mL (0.68 to 1.4 oz) aliquot of a PAM solution (Table 3). These aqueous solutions were made from simulated irrigation water and the same water-soluble PAM used in Experiment 1. This protocol simulated the field PAM treatments, which were applied to dry soils during furrow advance to reduce erosion. A constant 3.5 cm (1.4 in) head of simulated irrigation water was applied to each column using the constant head apparatus, and, after 25 to 40 minutes, the surface 6 mm (0.24 in) of soil was stirred with a bent wire to simulate the shear-induced soil disturbance caused by concentrated flow in furrows. After 1 hour, the percolation rate through the soils was measured. One hour later, all but 6 mm of the ponded water was suctioned from the cylinder and replaced with an aliquot of the second treatment solution (Table 3). Water flow was restarted, and percolation water was collected over 60-minute intervals during the subsequent five hours and at 19 hours after the second treatment. The completely randomized design included six treatments and three replicates per treatment. Analysis of variance tested for treatment effects. Mean separations for conductivity responses at 0 hours (initial flow measurement), 3-hour, and 19-hour times were determined at the P=0.05 probability level.

The effective saturated conductivity (K_s, mm h^{-1}) of soils was calculated as:

$$K_s = 10LV \cdot [At(H_2 - H_1)]^{-1} , \tag{1}$$

where L is the soil column length (cm); V is the water volume (mL) collected through the cross-sectional area A (cm^2) during time t (h); and (H_2 - H_1) is the depth of water (cm) ponded on the soil.

Experiment 3: Application uniformity in miniflumes. Miniflumes simulated furrow irrigation processes that occur in the field, but at a scale that permits laboratory testing. Various treatments were applied to miniflume soils in inflowing water, and their effect on runoff and infiltration along different quarter-sections of the minifurrows was evaluated. We constructed the 100 cm long (39.4 in), 8.5 cm wide (3.3 in), 15 cm deep (5.9 in) miniflumes from 6 mm thick (0.24 in) plexiglass (Figure 1). Three 3 cm tall dividers projecting up from the base partitioned the

Table 4. Treatments applied to miniflumes in Experiment 3.

	First treatment applied			Second treatment applied			
Treatment code	Material applied	Conc. mg L^{-1}	Furrow portion treated	Material applied	Type	Conc. mg L^{-1}	Furrow portion treated
Control	irrigation water	—	—	irrigation water	—	—	—
PAM10†	anionic polymer‡	10	entire	irrigation water	—	—	—
PAM125†	anionic polymer‡	125	upper 1/2	irrigation water‡	—	—	—
PAM500†	anionic polymer‡	500	upper 1/2	irrigation water‡	—	—	—
PAM10 + SLS§	anionic polymer‡	10	entire	Sodium Lauryl Sulfate	anionic surfactant	30 k	upper 1/2-3/4§
PAM10 + LIG§	anionic polymer‡	10	entire	Calcium Lignosulfonate¶	anionic surfactant	403 k	upper 1/2-3/4§

† PAM was applied with first water into th furrow and the flow of untreated irrigation water was continued immediately thereafter.

‡ Water soluble polyacrylamide: 13-15 Mg mol^{-1}; 18% charge density; Superfloc® 836A; CYTEC Industries, Stamford, Connecticut.

§ The initial PAM treatment was allowed to infiltrate. The 2nd treatment was applied, allowed to infiltrate, and the treatment was repeated. The flow of untreated irrigation water continued after the repeated 2nd treatment had infiltrated.

¶ Lignosite® 100; Georgia-Pacific West, Inc., Bellingham, Washington.

Table 5. Effect of treatment solution PAM concentration on infiltration through undisturbed soil cores, before and after stirring the surface 1 cm of soil (Experiment 1).

PAM	Infiltration rate		Difference value
Concentration mg L^{-1}	Before stirring surface mm h^{-1} (test for nonzero value†)	After stirring surface mm h^{-1} (test for nonzero value†)	Before minus after stirring mm h^{-1}
0	56a‡ (**†)	26b (***†)	30 a
10	74a (*)	38ab (**)	36 a
50	64a (*)	33b (**)	31 a
250	58a (*)	69a (***)	-11 b
500	17a (ns)	16bc (ns)	1 ab
Average < 250 PAM	64.8 A§	31.2 A	33.6 A
Average > 50 PAM	37.5 A	42.3 A	-4.8 B

† *t*-test for nonzero treatment mean, a *P*-value < 0.05 indicates that the infiltration rate was > zero. (*$P<0.05$; **$P<0.01$; ***$P<0.001$).

‡ Similar lower-case letters indicate nonsignificant differences between treatments in each column (P = 0.05).

§ Similar upper-case letters indicate nonsignificant differences between pooled low PAM treatments (0 to 50 mg L^{-1}) and pooled high-PAM treatments (250 & 500 mg L^{-1}).

box into four compartments, each with a drain on the downslope end. A 4 cm (1.6 in) layer of sand, then 7 cm (2.8 in) of Portneuf soil were lightly packed into the box, followed by a 3 cm (1.2 in) surface layer of non-packed Portneuf silt loam. A 1 cm deep (0.4 in), v-shaped "furrow" was formed in surface soil along the length of the miniflume. The slope was 7%. While this slope was not typical of furrow slopes in many irrigated areas, it was selected so that the average flow shear of the miniflume "furrow stream" would match that of field-scale furrows. (See Results and Discussion section.)

Flume inflow rate was 80 mL min^{-1} (2.7 oz min^{-1}). Drainage volumes from the four furrow quarter-sections and surface runoff were measured until they stabilized, ranging from 2 to 6 hours. Drainage and runoff rates and cumulative amounts were measured every 0.5 hours for 2 or more hours after runoff or drainage began. All treatments except the control included an initial PAM application to control erosion (Table 4). The PAM10 treatment was applied in advancing water, curtailed once runoff began, and followed immediately with untreated, simulated irrigation water. The PAM125 and PAM500 treatments differed from PAM10 in that concentrations were higher and only the upper half of the furrow was treated before continuing with untreated water. For PAM10+SLS and PAM10+Lig, the initial PAM10 dosing was allowed to infiltrate, the surfactant treatment applied, allowed to infiltrate and applied again. When the repeated

Table 6. Relative kinematic viscosity and substrate settling-rate transmittance comparisons for treatment solutions.

Material	Concentration mg L^{-1}	Relative kinematic viscosity†	Relative transmittance of suspension‡ — 3 hours after vortex mixing of solution and substrate: Portneuf SiL	Roza CL	KillPack Var SiL	Taunton LS
Irrigation water	—	1.00	100	13	100	69
PAM	10	1.02	100	46	100	89
PAM	50	1.30	89	16	51	82
PAM	125	1.86	85	8	28	89
PAM	250	1.93	61	8	9	89
PAM	500	4.00	69	5	3	84
PAM	1000	10.92	53	1.3	0.3	84
Irrigation water	—	1.00	47	12	82	81
Sodium Lauryl Sulfate	2.9 k	1.00	5	3	8	24
Sodium Lauryl Sulfate	29 k	1.23	12	4	75	38
Calcium Lignosulfonate	40.3 k	1.21	68	69	66	91
Calcium Lignosulfonate	403 k	18.1	100+	76	100+	100+
Sodium Lauryl Sulfate w/soil§	2.9 k	1.26	—	—	—	—
Sodium Lauryl Sulfate w/soil§	29 k	1.59	—	—	—	—

† Ratio of the kinematic viscosity of treatment solution divided by that of irrigation water. Viscosity was measured with Cannon-Fenske Type Viscometer, except for PAM solutions, for which viscosity was derived from concentration and temperature functions (Bjorneberg, 1998).

‡ A 0.2 g soil sample was added to 5 mL treatment solution and vortex mixed for 2 min, then allowed to stand undisturbed. Relative transmittance was computed as the transmittance measured through the suspension times 100 divided by maximum transmittance in an identical, but sediment-free, solution.

§ The treatment solution was mixed with 150g L^{-1} Portneuf soil, allowed to stand for 12 h, centrifuged, and the viscosity of the supernatant was measured.

dose had infiltrated, untreated irrigation water inflows were used to complete the run. For these two-stage treatments, the second applications were also made by treating the inflow streams, which were allowed to advance ½ to ¾ down the miniflume and infiltrate. This second treatment was repeated again, then untreated inflows were supplied to the flume for the remainder of the run. Inflows were adjusted 60 to 90 minutes into each run to prevent excessive runoff.

Irrigation uniformity along the miniflume was evaluated by examining the spatial difference between miniflume sections, which was calculated by subtracting the outflow-half drainage value from that of the inflow-half. The value for each half was derived as the mean of both quarter-section values. Difference values were calculated for the mean drainage rate at 165 minutes, cumulative drainage volume at 165 minutes, and cumulative drainage volume to 720 minutes. The 720 minutes cumulative drainage value was calculated by projecting forward from the last cumulative volume measured, assuming that the last measured drainage rate remained stable. The completely randomized experimental design included six treatments and three replications. The statistical analysis used the same approach as Experiment 1.

Experiment 4: Testing under pond seepage scenario (four soils). Treatment conditions for irrigation ponds and canals are different than for irrigation furrows. Amending large volumes of water needed to treat the wetted perimeter during the annual filling of irrigation ponds and canals may be cost-prohibitive. Instead, amendments can be applied to soil lining the pond or canal before wet up and allowed to dry before untreated water enters the structure. Because the first water that enters canals and ponds in the spring typically carries a heavy sediment load, the testing procedure needed to simulate this initial influx of sediment and accompanying turbulence.

We evaluated treatments with Portneuf silt loam, Killpack Variant silt loam, Tauntan loamy fine sand, and Roza clay loam. Columns were filled and packed with 100 g of the soil as done in Experiment 2. We then applied four treatment solutions to the surface soil using the same material from Experiment 2: PAM1000, 20 mL (0.7 oz) of 1000 mg L^{-1} (1000 ppm) anionic PAM; LIG403k, 20 mL (0.7 oz) of 403k mg L^{-1} (40.3% ai) calcium lignosulfonate; SLS29k, 20 mL (0.7 oz) of 29k mg L^{-1} (2.9% ai) sodium lauryl sulfate; and Control, no solution applied. Soils were air-dried for at least 24 hours, then saturated from below as in Experiment 2. A 500 g L^{-1} (50%) soil-water slurry was prepared from each soil being evaluated.

When the flow of irrigation water was started, 1.25 mL (0.04 oz) of the corresponding soil-water slurry was added to the ponded water. The water ponded above the soil was stirred vigorously for 3 s with a metal spatula to suspend soil fines and provide initial turbulence. The soil surface itself was not stirred as in Experiments 1 and 2. Twenty to 30 minutes after starting the flow, we began hour-long percolation volume measurements. A 0.25 mL (0.008 oz) aliquot of the soil slurry was added to the water ponded on the soil with stirring at the start of each hour, for six hours. Other 1-hour measurements were made at 7 hours, and at again 20 hours after the flow was started. The effective conductivity for treated soils was calculated at each measurement time using Equation 1.

The completely randomized design included the four treatments with three replicates per treatment. Analysis of variance tested for treatment effects. Mean separations for conductivity responses at 1, 5, and 20 hours were determined at the P=0.05 probability level.

Figure 2

Infiltration rate into undisturbed soil cores for various surfactant treatments measured before and after stirring the soil surface to 1 cm depth (Experiment 1). Similar upper-case letters indicate no significant differences between treatments before stirring, and similar lower-case letters indicate the same for treatments after stirring (P. 0.05).

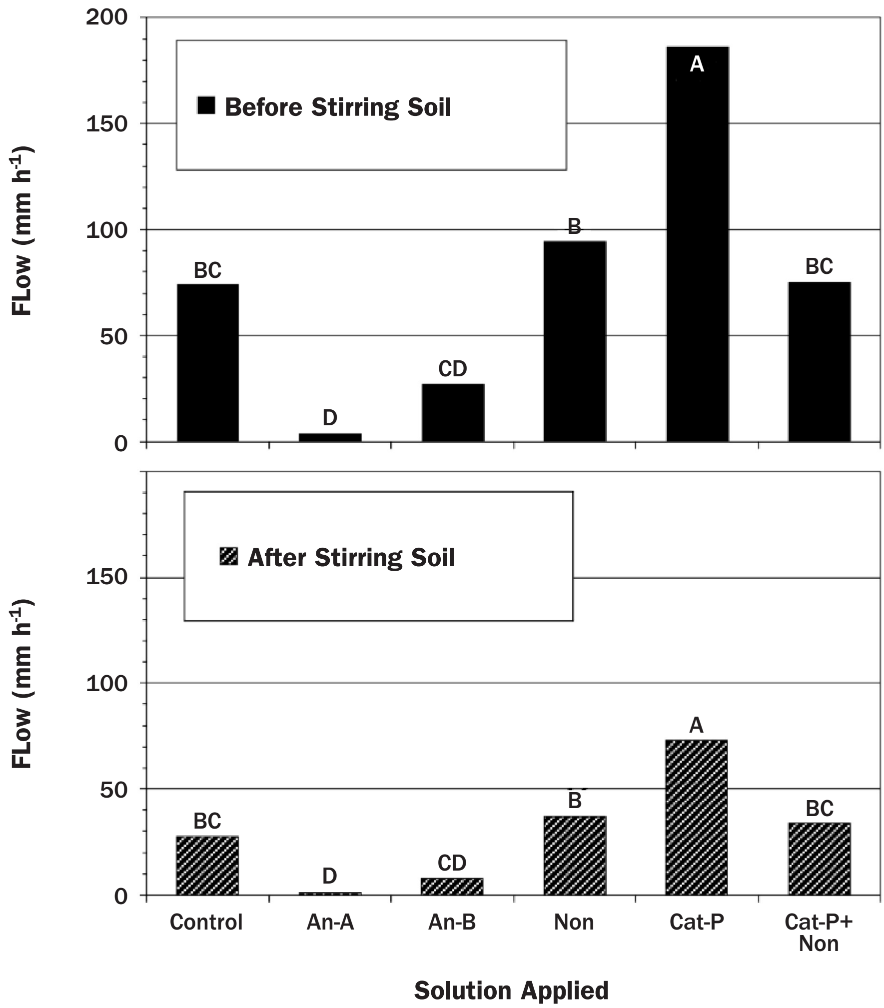
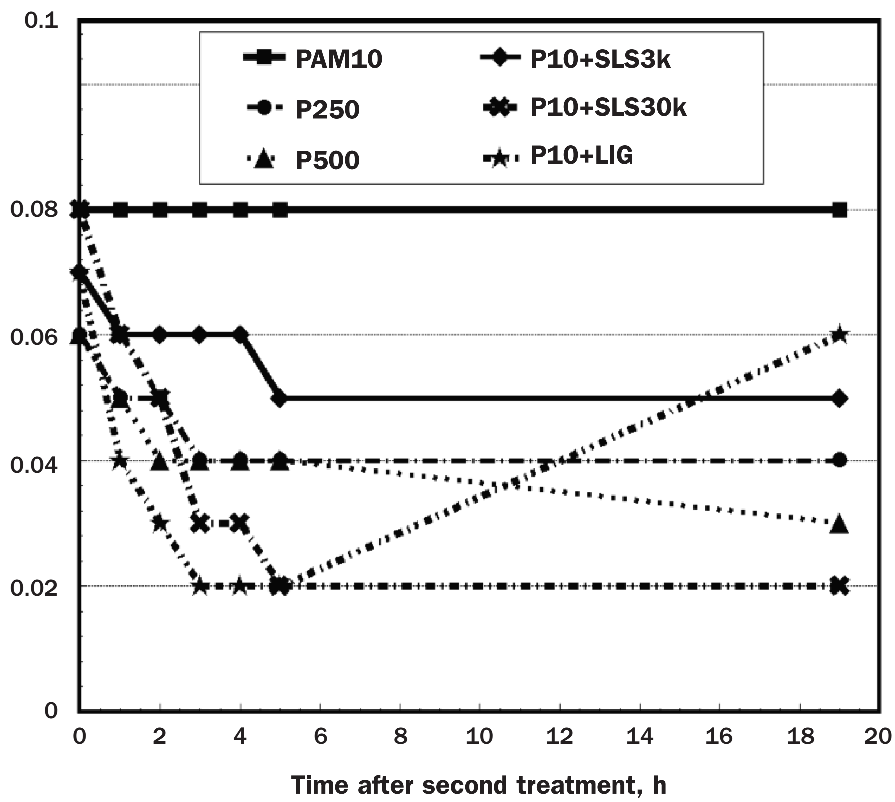


Figure 3
Effective hydraulic conductivity as a function of time under an irrigated furrow scenario (Experiment 2). Similar capital letters indicate no significant difference between treatment responses at any given time (*P.* 0.05).



Results and Discussion

Experiment 1: Evaluating PAM concentration and surfactant effects. In these structured intact soil cores, the relationship between treatment PAM concentration and water infiltration was statistically significant ($P < 0.05$), but only after the surface layer had been disturbed by stirring (Table 5). Before the surface soil in columns was disturbed, differentiation among treatments was difficult because flow variability among replicate soil columns was large. Small differences in the number or size of larger pores present in the unstirred surface soil had a large effect on infiltration among columns.

When the surface soil in the columns was stirred, the < 50 mg L^{-1} (<50 ppm) PAM treatments offered little resistance, and the soil broke up into dispersed particles and fine aggregates that became suspended in the ponded water. The 50 mg L^{-1} (<50 ppm) PAM treatment offered slightly more resistance to stirring and suspended fines settled to the soil surface within 30 seconds, 10 to 20x more rapidly than that of the 0 and 10 mg L^{-1} (0 and 10 ppm) PAM treatments. The 250 and 500 mg L^{-1} (250 and 500 ppm) PAM treatments offered noticeably more resistance to stirring, the soil broke up into cloddy chunks only, and no suspended fines were observed. Stirring the soil surface disrupted the continuity of larger pores and reduced flows by one-half in columns treated with lower PAM concentrations, but had little effect on flow rates for 250 and 500 mg L^{-1} (250 and 500 ppm) PAM treatments (Table 5). Stirring the 250 and 500 mg L^{-1} (250 and 500 ppm) PAM-treated surface soils created a layer of coarser aggregates with the same or a greater number of large pores than existed previously. This may explain why stirring appeared to increase flow in the 250 mg L^{-1} (250 ppm) treated soils.

Because stirring had no effect on flow in the 500 mg L^{-1} (500 ppm) PAM-treated soils, some factor other than soil aggregate size and porosity probably controlled infiltration. The viscosity of the 500 mg L^{-1} (500 ppm) PAM solution was 2x that of the 250 mg L^{-1} (250 ppm) treatment (Table 6) and may have been so great that the solution could not enter the smaller pores, and upon entering larger pores, flowed so slowly that conductivity was notably inhibited. If this supposition is correct, then increasing treatment PAM concentrations above 500 mg L^{-1} (500 ppm) should lead to greater infiltration-rate reductions.

The anionic surfactant treatments produced significant reductions in water flow relative to control soils (Figure 2). The flow rate through the anionic SLS-treated soil was < 5% of control values. As a single treatment, the nonionic surfactant had no effect on flow rate. When applied alone, the cationic polymer more than doubled the flow rate relative to controls; however, this flow-rate enhancement was negated when the polymer and nonionic surfactant were applied together.

Experiment 2: Testing under furrow irrigation scenario. Treatments applied to disturbed soil such as that in newly formed furrows affected water flow rates differently than when applied to the intact soil cores in Experiment 1. In the disturbed (packed) soil columns > 7 hours after surface stirring, the 250 and 500 mg L^{-1} (250 and 500 ppm) treatments reduced flows to half that of the 10 mg L^{-1} (10 ppm) PAM treatment (Figure 3), whereas the 250 mg L^{-1} (250 ppm) PAM treatment tended to increase flow relative to lower polymer concentrations for intact soil cores after surface stirring (Table 5). The apparent viscosity of PAM solutions increases with decreasing pore size (Malik and Letey, 1992). Thus, the viscosity effect associated with the higher concentration PAM solutions contributed to reduced flows in the packed columns because the largest contiguous pores in these soils were smaller than those present in the intact soil cores.

The P10+SLS29k treatment applied to packed soil columns (Figure 3) was only ¼ as effective as the SLS29k (An-A) applied to intact soil cores (Figure 2), for reducing water flow. The 10 mg L^{-1} (10 ppm) PAM pretreatment in the P10+SLS29k stabilized soil aggregates and better preserved soil porosity, especially macropores, after soil stirring. This apparently ameliorated SLS impacts on water flow.

A tenfold increase in SLS treatment concentration produced only a 2x greater reduction in water flow through the packed soil columns. A similar surfactant concentration effect was reported for loam soil (Allred and Brown, 1994). Note that the 29 k SLS solution was actually less dispersive and only

Table 7. Initial furrow advance, drainage rates and cumulative drainage amounts, and drainage differences between the inflow and outflow halves of the miniflumes.

Treatment	Initial furrow advance	Drainage rate @ 165 min		Cum. drainage @ 165 min		Cumulative drainage @ 720 min§	
		Mean	Diff.†	Mean	Diff.†	Mean	Diff.†
Code	min	mL min^{-1}		L		L	
Control	31 a	6.7 a	0.5 a ǂ	580 a	0.20 a	4400 a	0.41 a
PAM10	6 bc	5.8 ab	-0.9 b	420 ab	-0.11 bc	3490 bc	-0.55 b
PAM125	12 b	6.0 ab	-1.4 b	470 a	-0.34 c	3830 ab	-1.08 b
PAM500	3 c	4.8 b	-1.2 b	160 c	-0.32 c	2900 c	-0.89 b
PAM10 + SLS	3 c	2.4 c	-0.3 ab	0 c	0.0 ab	1220 e	-0.30 ab
PAM10 + LIG	3 c	3.1 c	-0.1 ab	40 c	0.03 ab	2080 d	-0.24 ab

ǂ Similar lower-case letters indicate nonsignificant differences between treatments in each column (P = 0.05).

† Difference value = inflow-half value minus that of outflow half. A positive number indicates that the drainage rate or cumulative amount produced in the inflow-half exceeded that of the outflow half.

§ Computed as a projection from the last cumulative volume measured and assuming the last measured drainage rate did not change further.

slightly more viscous than the 2.9 k solution (Table 6). This suggested that a process other than the clogging of pores by dispersed fines or viscosity-related inhibition was controlling water flow. Abu-Sharar et al. (1987) reported that reductions in conductivity resulted from aggregate collapse caused by slaking and the resulting destruction of large conducting pores. However, the pretreatment of soil with PAM is known to stabilize aggregates against slaking. Allred and Brown (1994) concluded that conductivity losses in loam soil leached with SLS was primarily caused by precipitation of calcium-surfactant salts. A dispersed fine white precipitate was observed in the first water ponded over the P10+S29k treated soils, indicating that precipitation of SLS was probably occurring here, as well. Because both SLS treatment solution concentrations exceeded the surfactant's critical micelle concentration (CMC), it is also possible that a greater number of colloidal-sized surfactant clusters, or micelles, formed in the higher concentration treatment and that their presence inhibited flow in the small pores of the soil or physically clogged soil pores (Miller et al., 1975).

The inexpensive calcium lignosulfonate application (P10+LIG) produced a 75% reduction in flow initially, at 4 hours, yet the effect was short-lived. By hour 19, the flow in the P10+LIG treated soils had risen to essentially the same rate as that for P10. The viscosity of the 403 k mg L^{-1} treatment solution was > 4x that of the 500 mg L^{-1} (500 ppm) PAM treatment; thus, a viscosity-induced reduction may explain the initial conductivity response. Unlike PAM, however, anionic surfactants are not strongly adsorbed to soil particles (Law et al., 1966). The concentration of calcium lignosulfonate in the soil pore water declined rapidly during the first 5 to 7 hours after application. This was evident because the dark brown color of the lignosulfonate leached from the soil in the initial percolating water cleared dramatically over time. Soil conductivity increased late in the test as soil solution viscosity declined. Because calcium lignosulfonate is more soluble and its critical micelle concentration is higher than that for SLS, the effect of Ca-LIG-precipitate and micelle formation on soil conductivity was less than that for the SLS treatment.

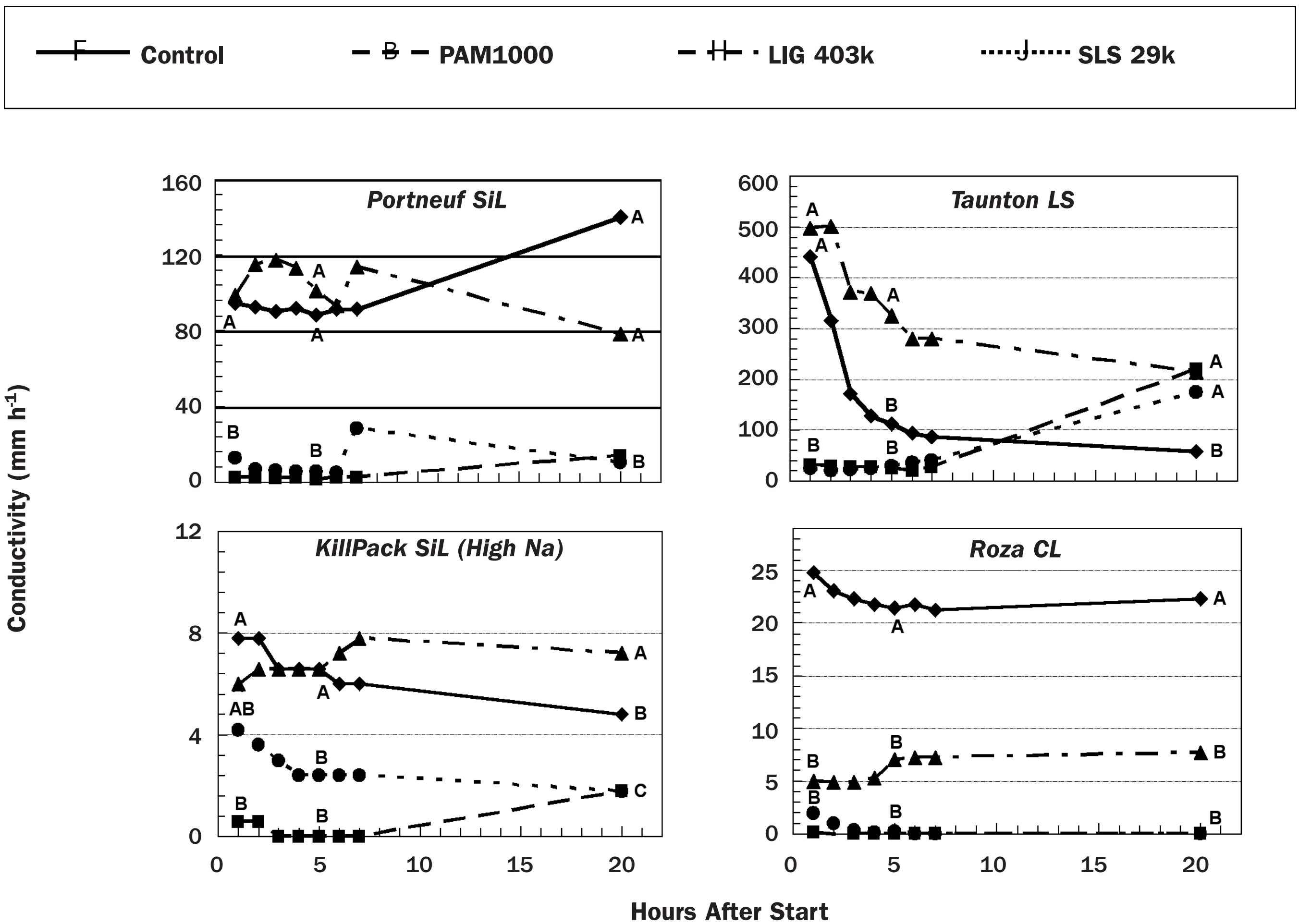
The higher concentration PAM and PAM+SLS treatments significantly reduced flow of water through disturbed soils and have the greatest potential for use in inhibiting infiltration in irrigated furrows and improving irrigation uniformity.

Experiment 3: Application uniformity in miniflumes. It was hypothesized that, with proper timing and loading, amendments added to irrigation water before it entered the field could be used to differentially treat the soils along the length of the furrow. PAM could be injected into initial irrigation inflows to attain a 125 to 500 mg L^{-1} (125 to 500 ppm) concentration (Experiment 2), and the injection curtailed when the stream advanced halfway across the field. The inflow-end furrow soils would be treated at full PAM concentration, but the outflow-half end would receive a successively smaller treatment with distance downstream, owing to the progressive dilution from inflowing, untreated water. Similarly, a 10 mg L^{-1} (10 ppm) PAM treatment could be applied to the furrow, followed by a surfactant treatment only to the inflow end of the furrow. Such treatments could alter application uniformity by decreasing infiltration at the furrow inflow end and either not affecting, or perhaps increasing, infiltration at the outflow end, relative to untreated furrow soils.

The miniflume tests demonstrated that untreated flows produced greater drainage rates and greater cumulative drainage amounts in the inflow half of the minifurrow than in the outflow half (Table 7). The three single-treatment PAM applications (PAM10, PAM125, PAM500) produced the reverse drainage pattern, with drainage rates and cumulative amounts being greater in the outflow halves, rather than inflow halves, of the miniflume. The PAM + surfactant treatments (PAM 10 + SLS and PAM 10 + LIG) produced the most uniform drainage pattern because these treatments produced the smallest absolute differences between inflow-half and outflow-half drainage rates and cumulative amounts. However, these dual-treatment difference values were not statistically different from that of the other treatments in most cases (Table 7).

Care must be taken when interpreting miniflume results and extending them to full-scale furrows. The Manning's roughness coefficient for the miniflume channel, 0.09 to 0.16, and average shear of the flow, 0.9 to 1.1 Pa, compared favorably with those for full-scale furrows (Trout, 1992a, b), though flow velocities of mini-furrow streams, 0.02 to 0.04 m s^{-1} (0.07 to 0.13 ft s^{-1}), were an order of magnitude smaller than that of full-sized furrow streams (Trout, 1992a), and miniflume advance ratios (irrigation time/advance time) for the 12-hour (720 minutes) period exceeded 24, 6x to 8x greater than for full-scale, 12-hour long furrow irrigation sets. Sirjacobs et al. (2001) concluded that miniflumes well-simulated the effect of PAM on furrow erosion in the field. In this study, the

Figure 4
Effective hydraulic conductivity vs. time for four soils under an irrigation pond seepage scenario (Experiment 4). Similar capital letters indicate no significant difference between treatment responses at any given time (*P.* 0.05).



main limitation of the miniflumes lay in their inability to fully model the surface aggregate-breakdown and sealing processes that occur in full-scale furrows. This was evident because the untreated minifurrows had greater infiltration and slower advance than PAM10 minifurrows (Table 7), and the reverse was observed at field scale. Full-size PAM10-treated furrows typically have greater infiltration and slower advance rate than untreated furrows (Lentz and Sojka, 2000). The PAM10 typically enhances infiltration by stabilizing the soil surface against slaking and inducing formation of more conductive surface seals, relative to untreated irrigation furrows (Mitchell, 1986; Sojka et al., 1998).

A critical evaluation of miniflume results indicate that the PAM125 and PAM500 treatments hold the greatest technical potential for improving water application uniformity in full-sized furrows. They were able to produce a reversal in the minifurrow infiltration pattern at 165 minutes, relative to untreated runs. In view of the limitations of the miniflume simulations, however, it is expected that the magnitude of PAM125 and PAM500 treatment effects on infiltration uniformity in the field would be less than the dramatic reversal observed for miniflumes. If applied to farmers' fields, the PAM125 and PAM500 miniflume treatments would cost three to eight times more than what farmers pay for PAM erosion control treatments. However, ongoing field research suggests that the infiltration inhibiting mechanism is more sensitive to PAM concentration than to total PAM applied, suggesting that infiltration goals could be achieved using smaller applications of PAM.

Experiment 4: Testing under pond seepage scenario (four soils). Relative to the untreated controls at 20 hours, PAM1000 and SLS29K treatments reduced conductivity by > 99% for Roza clay loam, 90% for Portnuef silt loam, and 61% for KillPack Variant silt loam (Figure 4). Taunton loamy sand responded differently to these treatments. The PAM1000 and SLS29K reduced the conductivity of Taunton relative to controls immediately after wet up, but by 20 hours, treated soil conductivities were nearly 4x greater than that of the controls. The LIG403K treatment decreased effective conductivity of Portneuf by 42% and 68% for Roza, but, unlike the other treatments, LIG403K ultimately increased conductivity for both the KillPack Variant (1.4x) and Taunton (2.8x) compared to untreated soils.

During the initial hours of each run, sediment stirred into the ponded water of PAM1000 and SLS29k columns formed more dispersed suspensions than for other treatments. By contrast, sediment stirred into LIG403k columns was flocculated and rapidly settled to the soil surface. Apparently, the initial water ponded on treated soils dissolved residual amendments present on the surface, and the concentrations during the first few hours were sufficient to induce the observed affects. The dispersion and flocculation effects noted in the columns were congruent with results from the settling and dispersion tests (Table 6).

Conductivity of all untreated soils decreased over the 20 hours; a phenomenon that has been attributed to several processes that influence soil porosity, including depositional seal formation (Shainberg and Singer, 1985), the destabilization and slaking of aggregates (Abu-Sharar et al., 1987) and soil consolidation (Trout, 1990). Amendments may alter conductivity by amplifying or inhibiting these processes.

To explore the effect of added sediment on soil conductivity, two additional treatments were applied to Portneuf soil columns. A 20 mL (0.7 oz), 500 mg L^{-1} (500 ppm) PAM solution was applied in both treatments, but one added sediment to ponded water and the other did not. Effective conductivity of the sediment-free treatment was 85 mm h^{-1} (3.3 in h^{-1}), vs 30 (1.2) for the sediment application. The sediment settled to the soil surface, clogged soil pores, and formed a depositional seal. Shainberg and Singer (1985) demonstrated that dispersed clay and silt produced depositional seals with significantly lower permeability than seals formed from similar flocculated particles.

The change in patterns of conductivity over time as a function of soil type suggested that specific treatment impacts varied with soil pore-size distribution. The smaller the average pore size of the soil, the more effective and enduring the conductivity reduction produced by the PAM1000 and SLS29K treatments. The observation that the PAM1000 conductivity reduction effect appears to wane with time and that this decline becomes more rapid as soil texture becomes coarser, suggests that the treatment does not permanently alter the physical structure of the soil. This supports the supposition that PAM1000 increases the viscosity of the soil solution (Malik and Letey, 1992), and this effect fades as the concentration of the material in soil pores is diluted or removed in drainage water.

The SLS29K treatment, like the PAM1000, produced an immediate reduction in conductivity, but the magnitude of this reduction trend was lower during the first 3 to 4 hours. This would be consistent with the hypothesis that an incremental build up of calcium-surfactant precipitate in soil pores reduced conductivity. The conductivity increase for SLS29K in loamy sand between 7 and 20 hours may indicate a dissolution of the precipitate with time. The SLS29K produced a proportionately smaller conductivity reduction in the high sodium silt loam soil (KillPack Variant) than for Portneuf silt loam. The SLS29K solution flocculated KillPack Variant soils more effectively than Portneuf (Table 6). This may have partially compensated for the viscosity and precipitation-related mechanisms that were acting to reduce soil infiltration rates in KillPack Variant soils. The strong conductivity reduction achieved by SLS29K in the Roza CL cannot be attributed to Ca-SLS precipitation because the calcium availability is low (Table 1). The surfactant's dispersive properties and Roza's high soil-clay content may have led to the formation of an impermeable depositional seal. Because the soil pH was < 7, SLS may have hydrolyzed to form lauryl alcohol. This water-insoluble oil may have imparted a hydrophobic character to the soil and inhibited water flow (personal communication, M.J. Rosen, 2002). However, a simple laboratory test showed that little or no lauryl alcohol formed in a SLS29K treatment solution when its pH was reduced to 6.5. Thus, the alcohol-formation mechanism probably did not play a role in inhibiting infiltration in the SLS29K-treated Roza soils.

The conductivity response patterns produced by the calcium lignosulfonate treatment may be the result of two processes. Initially, a viscosity-induced reduction could explain the low conductivity in treated fine and medium-textured soils relative to untreated soils. This reduction was not as great as seen in Experiment 2 because a portion of the lignosulfonate was sequestered in dead-end pores during the drying period after application and hence, solution concentration and viscosity in conducting pores was lower than that in Experiment 2. The effects of solution viscosity declined after 2 to 4 hours, owing to dilution. In soils that were particularly sensitive to soil dispersion, calcium lignosulfonate's flocculating effects eventually resulted in an increased conductivity compared with untreated soils. Thus, calcium lignosulfonate's flocculation and aggregate stabilizing habit helped to ameliorate the dispersing effects of sodium in KillPack Variant soils, and the pore-plugging effects of translocated silt and clay in the Taunton soil. This eventually led to increased water flow above that of controls (Figure 4).

Summary and Conclusions

Previous research has shown that high molecular weight, water-soluble, anionic polyacrylamide treatments tend to increase water infiltration into structured soils, relative to untreated counterparts. Principally, this occurs when structured, dry soils containing dispersible fines, are treated with PAM at solution concentrations of 20 to 500 mg L^{-1} (20 to 500 ppm) and allowed to dry, or applied to dry soils at concentrations of 1 to 20 mg L^{-1} (1 to 20 ppm) just before irrigation. PAM maintains higher infiltration rates in structured soils by preserving soil structure during rapid wet up and by inhibiting soil dispersion and surface seal formation. If the soil structure is lacking or has been degraded before treatment or soils are coarse-textured sands, lacking dispersible fines, adding anionic PAM to irrigation water can decrease infiltration relative to untreated soil. The infiltration reduction is greater with increasing concentration and viscosity of the PAM solution.

This research identified PAM application protocols that inhibited infiltration through structured soils, relative to controls. When I applied 1000 mg L^{-1} (1000 ppm) PAM solutions to dry silt loam and clay loam soils and allowed them to air dry, water flow was reduced by 60% to >99%. When applied to dry soils at concentrations of >125 mg L^{-1} (>125 ppm) just prior to irrigation, PAM demonstrated a potential for increasing furrow water application uniformity. Similarly, a 29 k mg L^{-1} (2.9% ai) sodium lauryl sulfate solution treatment reduced water flow by 90% or more relative to untreated soils. Under appropriate conditions, both high molecular weight anionic PAM and/or surfactant treatments potentially may be used for reducing unwanted canal and pond seepage and improving furrow irrigation uniformity. Because the amount of infiltration reduction achieved was a function of soil texture and Na content, these factors need to be considered when treatments are applied in the field.

Because PAM is already being applied to control erosion in furrow-irrigated fields, it appears to a good choice for further field studies. Ongoing research is addressing two concerns: 1) concepts successfully demonstrated in columns and miniflumes are being verified in full-scale furrows and irrigation ponds, and 2) alternate application protocols that require much lower PAM application amounts than that used in miniflume treatments are being evaluated in farm-scale furrows. Preliminary results from this ongoing research are encouraging and will be the subject of a future publication.

Endnote

[1]Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture-Agricultural Research Service and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

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